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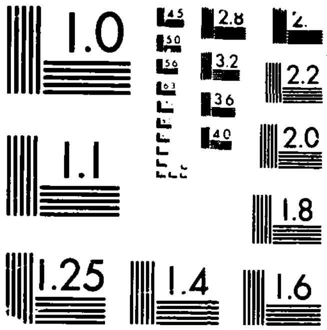

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 20506.11-GS
6a. NAME OF PERFORMING ORGANIZATION Thayer School of Engineering; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office
6c. ADDRESS (City, State, and ZIP Code) Dartmouth College Hanover, NH. 03755	7b. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U. S. Army Research Office; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAG29-84-K-0031
8c. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO / PROJECT NO / TASK NO / WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
The Tensile Strength of Ice Containing Cracks

12. PERSONAL AUTHOR(S) Erland M. Schulson

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 4/1/84 TO 12/31/87	March 8, 1988	8

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
ice, strength, cracks, tension, compression, notches, end constraint.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Experiments have established that long, sharp cracks reduce the uniaxial tensile strength of equiaxed and randomly oriented aggregates of fresh-water ice strained at $10^{-3}s^{-1}$ at -10°C, and that this reduction is in keeping with the dictates of linear elastic fracture mechanics. On the other hand, short cracks or long cracks that have blunted by creep deformation have no effect on strength. In the latter cases, the tensile strength is controlled by the nucleation of new cracks and not by the propagation of pre-existing ones.

Experiments have established also that the brittle compressive strength, σ_c, increases markedly with decreasing temperature but decreases with increasing strain rate. These effects are attributed to the controlling influence of shear crack sliding and, in turn, to the effects of temperature and sliding velocity on the coefficient of sliding friction, μ. The ratio of the compressive to the tensile strength appears to increase from around 8 at -10°C to around 15 at -50°C and is governed primarily by μ since, relative to the variation in σ_c, the tensile strength per se appears to vary little with temperature and strain rate.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. ABSTRACT

End constraint which imparts a radial compressive stress to ice raises the brittle, compressive strength slightly and promotes crushing through shear faulting. End constraint which imparts a radial tensile stress lowers the strength slightly and promotes crushing through axial splitting.

Finally, a circumferentail notch raises the tensile strength of coarsely grained ($d>3$mm) ice strained slowly ($\approx 10^{-7}s^{-1}$) at -10°C. This effect is attributed to the suppression by the notch-induced triaxial tensile stress of crack nucleation ahead of a creep-blunted notch.

ARO 20506.11-GS

THE TENSILE STRENGTH OF ICE CONTAINING CRACKS

Final Report

Erland M. Schulson

March 8, 1988

U.S. Army Research Office

Contract No. DAAG29-84-K-0031

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1. INTRODUCTION

This report summarizes the results of an experimental study on the mechanical properties of fresh-water ice. The work was performed during the period April 1, 1984 - December 31, 1987, and was designed primarily to determine whether pre-existing cracks affect the tensile strength. It was also designed to measure the brittle compressive strength and (from results (1-3) obtained under an earlier ARO-funded study) to determine the ratio of the compressive to the tensile strength of crack-free ice.

During the investigation the question of notch strengthening arose. Ceramics exhibit this effect, and so it seemed that ice might too. The question of end-constraint and a possible effect on brittle compressive fracture also arose. Rocks and brittle steel display an effect and so again it seemed that ice might. Thus, additional work was performed (supported in part by the ARO) and is summarized here.

2. THE TENSILE STRENGTH OF CRACKED ICE

Experiments were performed using large, cylindrically shaped specimens (10 cm dia. X 25 cm) of equiaxed and randomly aggregates of fresh-water ice prepared (as described elsewhere (1-3)) in the laboratory from distilled, deionized and degassed water. Initially, cracks were introduced by radially compressing the specimens over part of their mid-section using a specially built pressure cell and by monitoring the process by monitoring accoustical emissions. Subsequently, cracks were introduced simply by straining the specimens in tension at 10^{-7} s^{-1} at -10°C. The latter procedure has the advantages of greater control of crack number density and of less elapsed time (during which healing could occur) between crack nucleation and subsequent propagation.

The pre-cracked specimens were strained to fracture at -10°C at 10^{-3} s^{-1}. Under these conditions the strength of crack-free material of grain size from about 1 mm to about 10 mm is controlled by crack nucleation (3).

The results are detailed in a manuscript which has been submitted for publication ("The Tensile Strength of Cracked Ice"). They may be summarized as follows:

(i). Long, sharp cracks reduce the tensile strength. " Long" in this sense means a crack diameter equal to or greater than $2c_c$ where

$$2c_c = \frac{\pi}{2}\left(\frac{K_{IC}}{\sigma_o + k\, d^{-1/2}}\right)^2 ;$$

$\sigma_o = 0.51$MPa and $k = 0.03$ MPa $\bullet$ $m^{1/2}$ at $\dot{\varepsilon} = 10^{-3}s^{-1}$ (ref. 3); $K_{Ic} = 0.058 + 0.041\, d^{-1/2}$ MPa $\bullet$ $m^{1/2}$ for grain size, d, in mm (4).

The reduction in strength at -10°C at 10^{-3} s^{-1} may be expressed by the relationship :

$$\Delta\sigma_T = \sigma_o + (k - (\pi / \alpha)^{1/2} K_{Ic})\, d^{-1/2}$$

where $\alpha = 3.6 \pm 0.7$ and is the constant of proportionality between the grain size and the crack size, 2c.

(ii). When the existing cracks reduce the strength, the tensile strength is controlled by the stress to propagate those cracks and is given by the relationship:

$$\sigma_T^P = (\pi / 2)^{1/2} K_{Ic} (2c)^{-1/2} .$$

(iii). Short cracks or long ones that under load have been blunted by creep deformation at the crack tip have no effect on the tensile strength. In this case, the strength is controlled by the stress to nucleate a fresh crack and is given by the relationship:

$$\sigma_T^N = \sigma_o + k\, d^{-1/2}$$

where the parameters and their values are the same as noted above.

3. THE BRITTLE COMPRESSIVE STRENGTH

Experiments under uniaxial compression were performed on the same material at -10°C and at -50°C at 10^{-3} s^{-1} and at -10°C at 10^{-3} s^{-1}. The grain size was varied from about 1.5 mm to about 9 mm.

A preliminary account (5) of the work has been published. The results may be summarized as follows:

(i). Under high-rate compression where ice exhibits brittle behavior, fracture is more complicated than under tension. Crack nucleation and propagation are still important, but now ice-on-ice sliding across the opposing faces of shear cracks and the attendant frictional resistance to sliding become important. Also important is the formation within the tensile stress fields at opposite ends of loaded shear cracks of axially aligned wings or out-of-plane extensions to the shear cracks. Important, too, are the stable crack growth under increasing applied stress and the interaction of one crack with another.

(ii). These considerations and the experimental data reveal that the unconfined brittle compressive strength, σ_c, of ice may be expressed by the relationship:

$$\sigma_c = \frac{Z\ K_{Ic}\ d^{-1/2}}{(1 + \mu^2)^{1/2} - \mu}$$

where

$$\frac{1}{\mu} = \tan\ 2\Psi_C\ .$$

where μ is the coefficient of friction of ice on ice and Ψ_c is the angle between the direction of the principal compressive load and the plane on which the shear stress effective in forming the wings is a maximum.

(iii). An important implication of the above model is that the coefficient of sliding friction has a major effect on the brittle compressive strength . The increase in its value with decreasing temperature is the primary reason for the marked (i.e., 2.5 X) increase in strength upon reducing the temperature from -10°C to -50°C (5). Similarly, the decrease in its value with sliding velocit at high velocities (6) is most probably the reason the strength falls by about 30% upon raising the strain rate from $10^{-3}\ s^{-1}$ to $10^{-1} s^{-1}$. These points are discussed at length in ref. 5.

(iv). The ratio of the compressive to the tensile strength appears to depend upon both temperature and strain rate. Although firm statements cannot yet be made owing to difficulties encountered in testing ice in tension at -50°C, preliminary data suggest that under conditions whe crack propagation governs the tensile strength, the ratio increases from about 8 at -10°C to about 15 at -50°C. This difference is attributed primarily to the drying up (i.e., increase in sliding friction of crack surfaces and thus to the increase in the compressive strength. The tensile strength appears to increase only moderately with temperature (2).

4. EFFECT OF END-CONSTRAINT ON BRITTLE COMPRESSIVE STRENGTH

Ice of the type described above was compressed at -10°C at $10^{-3}s^{-1}$ under four different end conditions:

1. ice bonded to stainless steel
2. ice bonded to Synthane (a phenolic resin strengthened with cotton fibres)
3. ice in direct(but not bonded) contact with a brass plate
4. as 3., but with a thin (0.2 mm) insert of latex rubber.

Seven tests were performed under each of these conditions.

The results showed that the fracture mode changes from shear faulting for conditions 1, 2 and 3 to axial splitting for condition 4. Correspondingly, the microcrack distribution, as revealed through high-speed photography, changes from a central concentration for conditions 1, 2 and 3 to an end-zone concentration for condition 4. When coupled with the fact that microcracks nucleate under shear stresses, these observations show that conditions 1, 2 and 3 impose a radial compressive stress and that condition 4 imposes a radial tensile stress within the specimen near its ends.

The brittle fracture strength is moderately affected by the end constraint. In order of condition 1 to 4, the strength falls from 6.36 ± 0.84 to 5.62 ± 0.73 to 5.23 ± 0.79 to 4.98 ± 0.90 MPa. The trend suggests a reduction in the magnitude of the compressive constraint in the order noted.

A note of caution is appropriate. These results may be applicable only to the specific kind of ice tested under the specific conditions noted. Columnar ice, for instance, may exhibit a greater effect.

The work is currently being prepared for presentation at and for publication in the proceedings of the 9th I.A.H.R. symposium on ice, to be held during August 1988.

5. NOTCH STRENGTHENING

Tensile tests were performed on circumferentially notched and unnotched specimens of the above type at -10°C stressed at a constant rate of 100 Pa s^{-1} (across the notched section in that case). The grain size was varied from 2.2 to 7.3 mm.

The strength of the unnotched specimens increased with decreasing grain size, d, according to a $d^{-1/2}$ relationship, in quantitative agreement with the results obtained from an earlier study (3) performed at a constant strain rate of 10^{-7} s^{-1}. In this case, as in the earlier one, the strength extrapolated to zero for $d^{-1/2} = 0$, suggesting that the strength was controlled by the propagation of cracks nucleated during straining.

Although scattered, the strength of the notched specimens also obeyed a $d^{-1/2}$ relationship. In this case, however, the strength extrapolated to 0.8 MPa for $d^{-1/2} = 0$ and the sensitivity of the strength to grain size was lower.

From a comparison of the strengths of the two kinds of specimen it was clear that the notch strengthened the more coarsely grained ice (0.90 ± 0.02 MPa vs 0.65 ± 0.05 MPa, d = 7.3mm) but had no significant effect on the strenth of the more finely grained material (1.04 ± 0.02 MPa vs. 0.96 ± 0.07 MPa, d = 2.2mm). In other words, the notch strengthening effect diminished with decreasing grain size, and disappeared when the grain size reached about 2 to 3 mm.

These results are described more fully in a manuscript ("A Notch Strengthening Effect in Freshwater Ice") which has been submitted for publication. The effect can be explained in terms of the suppression of crack nucleation (which is a shear process) by the triaxial tensile stress induced within the material ahead of the notch. In other words, the strength of the slowly loaded notched material is not controlled by the propagation of the circumferential notch as it is at higher stress rates, but by the nucleation of new cracks across the reduced cross-section.

The implication is that creep blunts the circumferential notch, just as it can blunt internal cracks in loaded ice (See Section 2). Calculations support this view.

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7. ACKNOWLEDGEMENTS

During the early part of this program, before Dartmouth's Ice Research Laboratory was operating, facilities of USA-CRREL were graciously made available to us. We gratefully acknowledge this co-operation.

Also, we acknowledge discussions with colleagues from CRREL, in particular, with Stephen F. Ackley, David M. Cole, Gordon F.N. Cox, Anthony J. Gow, and Jackie Richter-Menge.

8. PAPERS / MANUSCRIPTS STEMMING FROM PROGRAM

1. "The Characteristic Grain Size and the Compressive Strength of Ice Containing a Bimodal Distribution of Grain Size.
   E.M. Schulson and J.L. Laughlin
   J. Offshore Mech and Arctic Eng. (in press).

2. "The Tensile Strength of Cracked Ice I_h"
   E.M. Schulson and S.G. Hoxie
   Abstract EOS, 68, (1987), 1316.

3. "A Notch Strengthening Effect in Fresh-Water Ice"
   W.A. Nixon and E.M. Schulson
   Journal American Ceramic Society (submitted)

4. "The Tensile Strength of Cracked Ice"
   E.M. Schulson, S.G. Hoxie and W.A. Nixon
   Philosophical Magazine (submitted)

5. "The Mechanical Properties of Ice"
   E.M. Schulson
   As invited contribution to : Advances in Materials Science and Engineering: Supplementary Vol. of the Encyclopedia of Materials Science and Engineering
   (submitted June 1, 1987)

6. "The Fracture of Ice"
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